

FIG. 3. Density and expansion velocity of negative ions as function of laser energy at a distance of 5 cm from the target.

radius and the correct sense of rotation could reach the recessed collector which had an exposed area of  $7 \times 10^{-3} \text{ cm}^2$ . The probe shaft was solid copper and shielded the collector wire.

The detection of  $\text{H}^-$  was further distinguished from that of electrons by their longer time delay taken to reach the probe. The expanding velocity of  $\text{H}^-$  is measured by the time-of-flight method to be  $10^5 - 10^6 \text{ cm/sec}$  depending on the laser power as shown in Fig. 3. In this configuration an axial probe was used in conjunction with a magnetic field. To avoid too high an electron temperature near the target, which is unfavorable to the formation of  $\text{H}^-$  we have placed the target 1 cm away from the focal point. The illuminated area of the target is approximately 5 mm in diameter. Our measurements at various laser power levels summarized in Figs. 3 and 4. At lower laser energy the observed  $\text{H}^-$  density is higher while the expanding veloc-

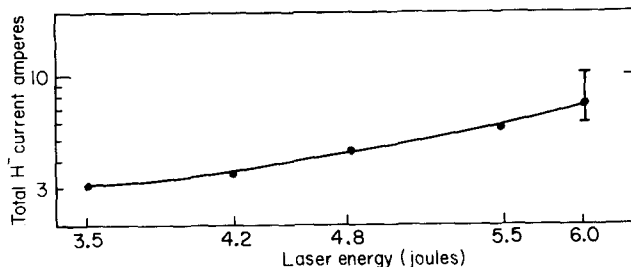


FIG. 4. Total negative ion current vs laser energy in joules at a distance of 5 cm from the target. Optimization of the target position and laser power could produce up to 10 A of  $\text{H}^-$  ions as shown by the solid vertical bar at the highest power.

ity  $V_d$  is lower. This agrees with Eq. (1) in that a lower  $T_e$  produces more negative ions.

Once the negative ions are produced, they can be accelerated to the desired energy. The electron bounded to this accelerated negative ion could be resonantly detached in the illumination of a laser beam of the appropriate wavelength ( $\approx 1.5 \mu$ ). Using a detachment cross section of  $10^{-17} \text{ cm}^2$  we compute that for an illumination length of 1 m a laser of  $35 \text{ kW/cm}^2$  is required. The required intensity might be achieved by reflecting the laser beam back and forth through the interaction region many times; in this way the required power should be in the range of  $1 \text{ kW/cm}^2$ .

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## Short $\text{CO}_2$ laser pulse generation by optical free induction decay

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Short  $\text{CO}_2$  laser pulses, adjustable in the range between 0.1 and 0.5 nsec, have been produced by a new pulse-shaping technique. A laser breakdown spark is the active switching element, but the pulse is actually generated by optical free induction decay in a passive linear medium. This approach features simplicity, fast rise time, high contrast ratio, unity switching efficiency, and is suitable as the input to high-power amplifier stages.

Although laser-induced breakdown has been an easily observed<sup>1</sup> and dramatic effect, it is only now beginning to find its way into applications. Recent experiments have shown that laser-induced breakdown in gases can be accompanied by substantial spectral broadening<sup>2</sup> and self-phase modulation.<sup>3</sup> These observations indicate that the plasma cuts off transmission of the incident beam in a time as short as 30 psec.<sup>2</sup>

The basic concept<sup>2</sup> of short-pulse generation from a laser spark is to employ a spectral filter which rejects the incident laser wavelength, but transmits the sidebands produced by the sudden plasma growth. Among the types of spectral filters which have been suggested are the Michelson interferometer,<sup>4</sup> the Fabry-Perot etalon,<sup>5</sup> and the grating monochromator.<sup>2,3</sup> Of these, only the grating device, especially in the form of a

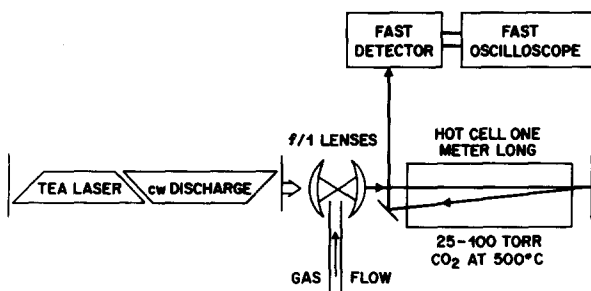


FIG. 1. Experimental apparatus.

double monochromator, has sufficient rejection ratio to be of practical interest. It is however an expensive and inconvenient instrument to use. The pulse shaper described in this paper uses resonantly absorbing CO<sub>2</sub> gas as the spectral filter.

The experimental arrangement is shown in Fig. 1. A conventional TEA double-discharge laser, of several MW output power is the source. An intracavity low-pressure cw gain cell<sup>6</sup> narrowed the output spectrum to one axial mode. The light was transmitted through a spherically corrected *f*/*1* lens pair, between which the spark formed. (Some of the measures which were taken to ensure a high nucleation intensity are described in Ref. 3.)

The light was then transmitted, in double pass, through a 1-m hot cell containing CO<sub>2</sub> gas. Both pyroelectric detectors and high-speed Ge Hg photoconductors monitored the output beam. Some oscilloscope photographs of output pulses are shown in Fig. 2.

It is intuitively satisfying to examine the pulse-forming mechanism in the time domain: The input beam is

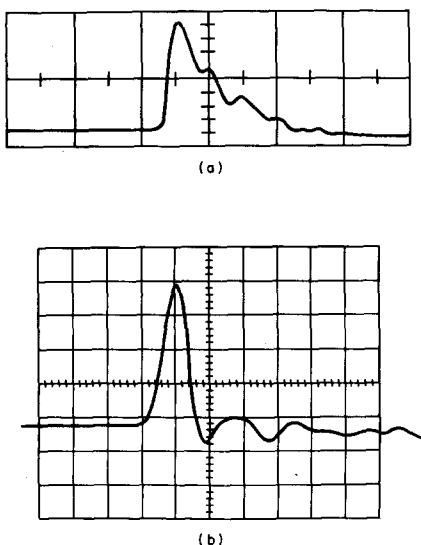


FIG. 2. The short pulse generated with 100 Torr of CO<sub>2</sub> in the hot cell as observed by two different detection systems. Neither system is capable of resolving the true pulse duration of ~150 psec. Both systems are troubled by electrical ringing on the trailing edge of the pulse caused by the sudden transient. (a) 2 nsec/div. Monitored by a Ge:Hg photoconductor and a Tektronix 519 scope. Note the scope-limited rise time. (b) 1 nsec/div. Monitored by a pyroelectric detector on a Tektronix 7904 scope.

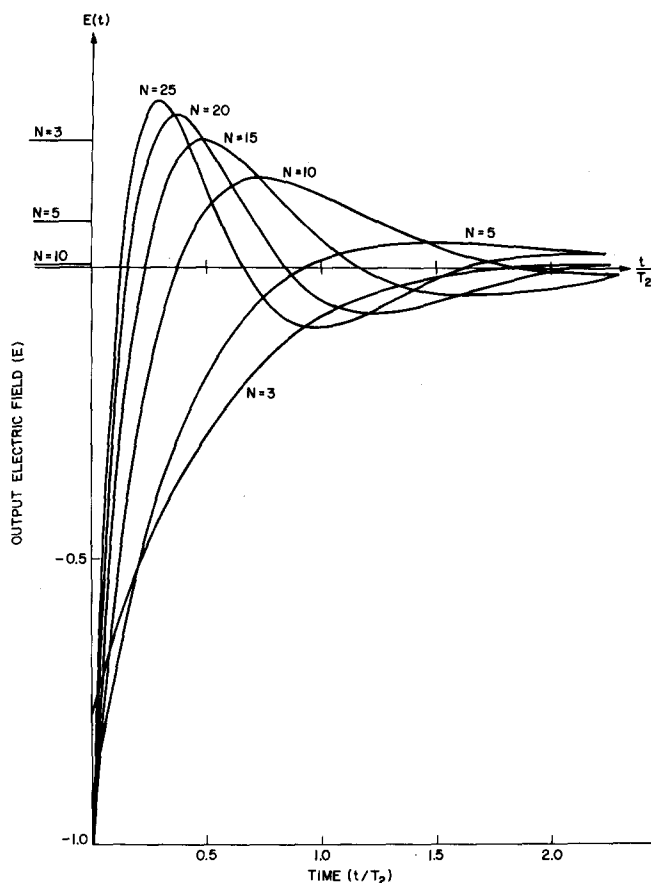


FIG. 3. Output electric field as computed by linear analysis on the Lorentzian line shape. For  $t < 0$  the input beam is simply attenuated. ( $N$  is the attenuation in nepers.) At  $t = 0$  the spark forms. For  $t > 0$ , a pulse is generated by optical free induction decay in the medium.

almost completely attenuated by linear absorption in the hot CO<sub>2</sub> gas. The output electric field may therefore be regarded as a destructive interference between the input field and the electric field generated by the induced linear polarization in the absorber.<sup>7</sup> Since the light is almost totally absorbed, the field generated by the medium is of the same amplitude as, but 180° out of phase with, the input wave. If the input wave is suddenly cut off, as by the breakdown plasma, the molecular polarization will continue to radiate its wave (which is no longer canceled by destructive interference) for a time related to the transverse relaxation time. The output is a pulse of essentially the same power as the input wave, opposite phase, and a duration of the order of the molecular collision time. Thus, the pulse is produced by optical free induction decay.<sup>8</sup>

The above considerations are confirmed by linear systems analysis in the frequency domain. Since the plasma growth is much faster<sup>2,3</sup> than all relaxation times in this experiment, it is sufficient to regard its effect as simply a step function cutoff of the beam. The Fourier amplitude of a step function is  $\sim 1/\Delta\omega$ , where  $\Delta\omega$  is the frequency shift from line center. This should be multiplied by the transmittance function  $T(\Delta\omega)$  of the resonant medium to obtain the Fourier spectrum of the output light:

$$T(\Delta\omega) = \exp[-N/2(1 + i\Delta\omega T_2)].$$

$T$  has a Lorentzian character and describes both the absorption and phase shift of the medium.  $N$  is the attenuation in nepers and

$$1/\pi T_2 = 7.58(300/T)^{1/2} \text{ MHz/Torr}$$

is the full width at half-maximum of the homogeneously broadened line.<sup>9</sup> ( $T$  is the absolute temperature of the  $\text{CO}_2$ .) The inverse Fourier transform may be performed analytically<sup>10</sup> to yield the following form for the electric field amplitude of the output pulse in time:

$$E(t) = -\int_y^\infty \exp(-y^2/2N) J_1(y) dy \\ = \exp\left[-\frac{N}{2}\right] - \exp\left[-\frac{t}{T_2}\right] \sum_{m=0}^\infty \left[\frac{2t}{NT_2}\right]^{m/2} J_m(y),$$

where  $y = (2Nt/T_2)^{1/2}$  and  $J_m$  is the Bessel function of first kind of order  $m$ . This is plotted in Fig. 3 for various values of the parameter  $N$ . Note that the output field reverses phase at the instant the spark forms, confirming our intuitive discussion.

At  $t=0$ ,  $|E(0)| = |1 - \exp(-N/2)|$ , and therefore the efficiency of the pulse shaper,  $|E(0)|^2$ , is essentially unity when  $N$  is large. The rise time is instantaneous on the time scale of this experiment, as already discussed. The pulse duration  $\approx T_2/N$  is adjustable in the range 0.1–0.5 nsec by simply changing the gas pressure.

This technique is unique in that the output field shape and duration are analytically determined by the linear optical properties of a passive medium. Moreover, since the pulses are generated by a linear polarization, they are also exceptionally clean, predictable, and reproducible. These advantages are important for applications ranging from nonlinear optics to laser fusion. Furthermore, the concept may be extended to any laser wavelength, and more importantly to any linearly absorbing material, for the purpose of producing a wide variety of transient waveforms.

An important pulse parameter, especially for injection into a high-gain saturating amplifier chain is contrast ratio; i. e., the ratio between the peak power and the power in the inevitable precursor. This is determined by our ability to absorb the unshifted laser light before the spark forms. The absorption coefficient of the  $\text{CO}_2$  gas is increased by raising the temperature to populate the lower laser level. The maximum absorption of about 10 dB/m occurred near 500 °C.<sup>11</sup> Above 20 Torr the lines are homogeneously broadened and the absorption coefficient is independent of pressure. In this experiment the rejection ratio was  $10^2$  since only a 2-m path was used. In a 6-m path the ratio would be  $10^6$  which is higher than can be achieved electro-optically. Saturation of the absorption cell should be avoided

for the free induction decay to be in the linear regime and to ensure that the maximum possible contrast ratio is obtained.

Since the spectrum induced by the laser breakdown spark is so broad,<sup>3</sup> our pulse-forming technique is compatible with multirotational-line operation of a high-pressure  $\text{CO}_2$  amplifier. This is important for exploiting the efficiency of which these amplifiers are capable.<sup>12</sup>

In summary, we have produced short laser pulses by a versatile technique based on a laser breakdown spark as the active switching element, and the optical free induction decay of a linear polarization in a passive medium. Since the generation mechanism is linear, the pulses are exceptionally clean, predictable, and reproducible.

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